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# *Mechanical Properties of Solid Foods—*
# *Deformation, Fracture and Stress Relaxation*

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## SUMMARY

*The structural and compositional complexities of solid foods make it*
*advantageous, perhaps essential, to evaluate their mechanical properties by*
*more than one experimental technique. By comparing results from different*
*testing modes, problems in methodology may be discovered and lead to a*
*greater understanding of the mechanical behaviour and of the structure/*
*composition/processing interrelationships. Foods that undergo relatively*
*large deformations before fracture present particular difficulties because of*
*time-dependent effects during measurement. Despite recent progress, such*
*materials, with behaviour governed by a broad spectrum of relaxation times,*
*need better quantitative methods of describing time effects in stress growth*
*during deformation and stress relaxation after deformation. The frictional*
*properties of foods need fuller investigation, to improve both understanding of*
*texture profile analysis tests and their relationship to sensory perception of*
*foods.*

## INTRODUCTION

Determination and evaluation of the physical properties of solid foods
present many difficulties to the scientist, as described so succinctly by Prins
and Bloksma (1983). Solid foods are often heterogeneous and anisotropic.
Sample history can be crucial, with results dependent not only on such
factors as rate and extent of deformation but also on the sample history,
which includes processing and storage effects prior to measurement.
Consider the determination of the response of a solid food to torsion. It is

necessary at some point to place the sample on an instrument between two parallel discs. In this manipulation, forces are exerted on the sample and it can take a considerable time for these forces to relax so that the stable baseline necessary for the actual experiment may be obtained. Not only is this time-consuming but, because of the high water activity of many food systems (for example gels), the sample may start to dry out. Crust formation can then lead to erratic results. Humidity control is then necessary to prevent sample drying. Depending on the actual equipment being used, humidity control is not always easy.

Another problem can be that of attaching the sample to an instrument. For example, in experiments by Navickis and Bagley (1983) on a solid material consisting of a close-packed dispersion of swollen starch particles, the sample was placed between metal platens and large deformations applied in simple shear. Initial shear stress/shear strain results were erroneous because the sample slipped on the plates. The problem was detected only because the results, superficially acceptable, were internally inconsistent. Resolution of the difficulty was achieved by bonding the sample to the instrument platens with a cyanoacrylate adhesive, which has since been shown to be an ideal material for bonding a wide range of food materials, including meats and water-based gels and dispersions, to metals.

On a more fundamental level, mechanical testing of solid foods is so broad in scope that it is essential to assess carefully the objectives of the work being undertaken. The scope may be relatively narrow, concerned, for example, with quality or process control, or it may be broader and deal with such problems as component interactions in complex mixtures. Notwithstanding limited immediate objectives, the range of application, and the implications, of technical results may develop beyond those limits. Opportunities present themselves and new avenues of approach are opened. The best way of ensuring the value and meaning of the results obtained in measurements on foods, therefore, is to discuss the 'deformation, fracture and flow of food materials in terms of fundamental units of physics' (Hamann, 1983). Sound engineering input is also needed, and this point was emphasised by Jowitt (1979) and Szczesniak (1977). Progress in polymer research and material science can provide guidance for food scientists in methodology and data analysis. Even though foods suffer from complexities which are usually not present in polymer systems (biological activity, for example), many useful techniques and concepts may be transferred from polymers and their blends, including composites, to food systems. Jowitt (1979) has discussed some aspects of this with reference to fracture processes and the behaviour of laminated food.

The objectives of this chapter are: to show the advantages of using various testing modes in evaluating the physical properties of foods; to examine strain and time effects; and to suggest some areas worthy of continued research effort.

# THEORETICAL BACKGROUND

## Stress–Strain Relations

There is extensive literature on the mechanics of polymers which is relevant to the consideration of the mechanical properties of foods. Useful references include Williams (1973) on stress analysis of polymers, Treloar (1975) on physics of rubber elasticity, and Kinloch and Young (1983) on fracture behaviour of polymers. Familiarity with the terminology and use of tensors is necessary for reading much of the rheological literature and a useful textbook in this subject area is provided by Darby (1976).

Rheologically, the question as to whether a particular food is a solid or a liquid should be considered in terms of the non-dimensional Deborah number, $D$, defined by Reiner (1964) as the ratio of the relaxation time of the sample divided by the time of observation. In Reiner's words: 'The difference between solids and fluids is then defined by the magnitude of $D$. If time of observation is very long or, conversely, if the time of relaxation of the material under observation is very small, you see the material flowing. On the other hand, if the time of relaxation of the material is larger than your time of observation, the material, for all practical purposes, is a solid.' Time is, in general, a crucial variable when investigating the mechanical properties of foods. It is necessary to determine not just a stress–strain curve but the stress–strain–time relationships describing the behaviour of the material. For complex foods there is an artificial distinction between solid and liquid states, which depends not only on the material but also on the experimental time scale relevant to the specific use of the food or the specific process to which the food is subjected.

There is no ambiguity in the definition of stress, the force per unit area. There are, however, various ways of defining strain. The classical definition of infinitesimal strain will normally be applicable only for small deformations. For large deformations Peleg (1984) has compared strain definitions such as Hencky's, Almansi's, Green's and Swainger's with the terms of Mooney's equation for compressive deformation. Mooney's two-term relationship, discussed by Peleg, is of particular interest as a special case of the more general approach to the large deformation behaviour of

isotropic materials as discussed by Rivlin in his review (1956) and applied to rubber-like materials by Treloar (1975). The value of the approach is that a stored-energy function, $W$ (from which the stress–strain response of the material can be derived), is written in terms of three strain invariants, $I_1$, $I_2$ and $I_3$. These invariants are defined as follows: A cube of side length 1 cm is deformed to dimensions $\lambda_1, \lambda_2, \lambda_3$. The strain invariants are then given as

$$I_1 = \lambda_1^2 + \lambda_2^2 + \lambda_3^2 \tag{1}$$

$$I_2 = \lambda_1^2\lambda_2^2 + \lambda_2^2\lambda_3^2 + \lambda_3^2\lambda_1^2 \tag{2}$$

$$I_3 = \lambda_1^2\lambda_2^2\lambda_3^2 \tag{3}$$

$I_3$ represents the volume of the cube after deformation and, if the material is incompressible, the value of $I_3$ during deformation is constant at unity. The stored energy function will then be given as

$$W = W(I_1, I_2) \tag{4}$$

If a form is assumed for the stored energy function, it becomes possible to calculate the expected stress–strain relationship for given deformation modes, such as simple shear, torsion, compression, extension, etc. A two-constant Mooney material is described by the strain energy function

$$W = C_1(I_1 - 3) + C_2(I_2 - 3) \tag{5}$$

For three common deformation modes—extension/compression, simple shear and torsion—the stress–strain relationships for a Mooney material assume the forms:

*Extension/compression*

$$f = 2(\lambda - 1/\lambda^2)(C_1 + C_2/\lambda) \tag{6}$$

where $f$ is the force per unit area measured in the unstrained state.

*Simple shear*

$$\tau = 2(C_1 + C_2)\gamma \tag{7}$$

where $\tau$ is the shear stress, $\gamma$ is the shear strain, and $2(C_1 + C_2)$ is the shear modulus, $G$. The material thus obeys Hooke's law in shear.

*Torsion*

$$M = \pi\psi a^4(C_1 + C_2) \tag{8}$$

$$N = -(\pi/2)\psi^2 a^4(C_1 + 2C_2) \tag{9}$$

where $M$ is the torque, $N$ is the normal stress, $\psi$ is the torsional strain $(\psi = \theta/h$, $\theta$ being the angle of twist and $h$ the sample height), and $a$ is the sample radius.

The assumption that the stored energy function can be described by eqn. (5) is restrictive and, as Treloar (1975, Chapter 10) comments, 'great care must be exercised in drawing general conclusions from the apparent agreement with the Mooney theory obtained experimentally'. He goes on to note that any particular type of strain provides too narrow a basis for determining the true form of $W$. Nevertheless, the relationships given by eqns. (6)–(9), based on the Mooney theory, are excellent starting points for considering experimental data from different test modes. Deviation of experimental results from expected values necessitates a more general treatment of the data involving derivatives $(\partial W/\partial I_1)$ and $(\partial W/\partial I_2)$ rather than $C_1$ and $C_2$. It is only by considering all types of strain over a wide range that a true assessment of material properties and not one limited by a particular test can be expected. Hamann has also commented on the need for results which are not dependent on a specific test geometry (Hamann, 1983) and compared the results of structural failure in simple shear, torsion and uniaxial compression using Mohr's circle procedure.

### Time, Yield and Fracture Effects

Solid foods will often show complex time effects, as illustrated by Olkku and Sherman (1979) (their Figs. 12 and 13). These show stress–strain response curves for liquorice. It is sometimes convenient and useful when considering a large quantity of rate-, time- and deformation-dependent data to use rheological models to describe the material's response. As in the polymer field, various combinations of Maxwell and Voigt elements, as well as other combinations of springs and dashpots, can be used to develop equations to reduce data quantitatively. Peleg and colleagues have been major proponents of this approach, but in treating mechanical properties of solid foods they have found it necessary to add contact and fracture elements to the more common linear viscous and elastic elements to explain the various memory phenomena observed (Peleg, 1977; Pollak and Peleg, 1980). The paper by Calzada and Peleg (1978) demonstrates clearly the type of stress strain/strain rate responses observed in such diverse materials as bread, turnip, bologna sausage and squash. Peleg and co-workers have also shown the advantages of computer-aided characterisation and classification of solid foods (Miller *et al.*, 1986; Peleg and Normand, 1982; Purkayastha *et al.*, 1985), while keeping in mind the need to relate the results to sensory perception (Peleg, 1980a, 1978).

Time effects, both during and after deformation (as in stress relaxation studies), are important in many food systems. As Feltham (1955) expounded, there is 'remarkable qualitative similarity in the response of solids of widely different structures', including polymeric solids, ceramics and other materials whose log-normal distribution of relaxation times leads to linear stress relaxation plots on probability paper. The method has been used in food materials by, for example, Shelef and Bousso (1964). Peleg (1980b) and Peleg and Normand (1983) compare other methods for obtaining linear stress relaxation and creep curves, but there are fundamental issues which need greater attention. The problem is that stress relaxation curves depend on the time it takes to deform the sample. Thus, if a deformation is completed in $t_1$ s, then the 'rule-of-ten' requires that only relaxation data at times greater than $10t_1$ be used in analysing the results. The problem is not easily dealt with but the paper by Meissner (1978) shows one method of treating stress relaxation in polymeric liquids and solids by assuming that the materials are linearly viscoelastic and the strain history is one of constant strain rate in the period $0 < t < t_1$ followed by a constant strain for $t > t_1$. Other approaches which have not been applied to solid foods but which show promise include the use of an integral constitutive equation as, for example, in the work of Zapas and Phillips (1971).

**Complementary Testing Modes—Some Experimental Results**
Gels are of particular interest because their mechanical behaviour should be described by rubber-like elasticity theory, specifically by the Mooney two-constant equation. Attention should be given to the review of gel behaviour by Mitchell (1976) and to recent original contributions (Sherman, 1982; Ring and Stainsby, 1982; Richardson et al., 1981; Dahme. 1985; McEvoy et al., 1984). These works indicate the long-term and continuing activity which exists in the examination of the physical properties of gels and gel-like foods. A surprising result was obtained at the author's laboratory when carrying out experiments on the behaviour of gelatin gels in simple shear, torsion and compression. It was found that the material followed the Mooney equation in two of the modes, simple shear and torsion, but showed very large deviations from the expected behaviour in compression (Bagley et al., 1985a). The problem was traced to frictional losses at the sample/platen interface during compression. Elimination of these effects by either lubricating or bonding the surfaces of the samples in contact with the compression plates yielded results in complete agreement with those from simple shear and torsion experiments (Bagley et al., 1985b).

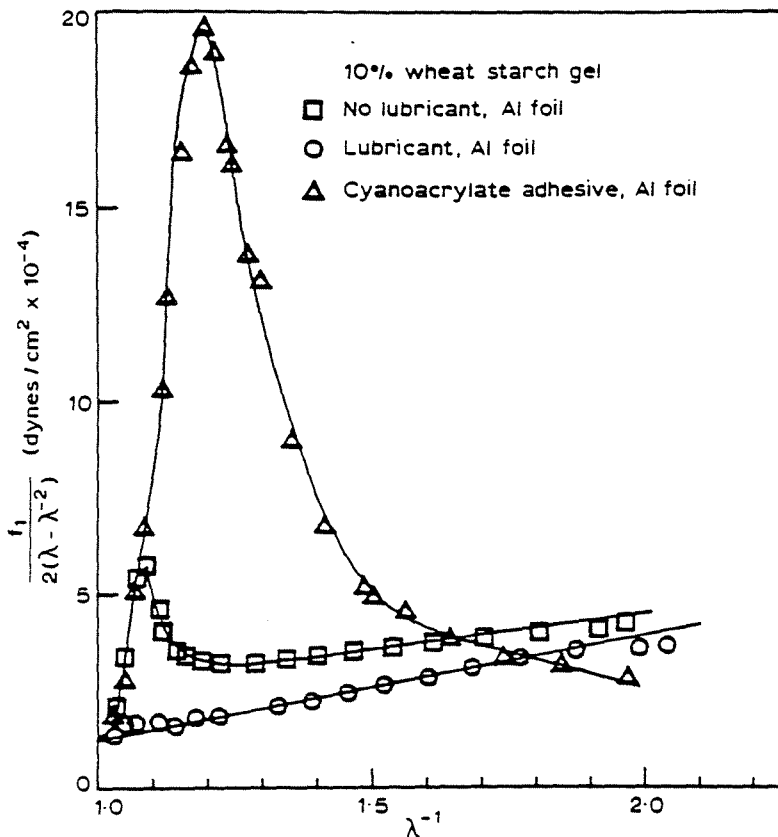The magnitude of frictional effects in uniaxial compression of wheat

Fig. 1. Uniaxial compression of cylinders of a 10% wheat starch gel using aluminium foil as interface between platens and gel. Upper curve is the response when the gel is bonded to the aluminium foil; middle curve, neither bonded nor lubricated; lower curve, lubricated between gel and aluminium foil. Nominal radii and heights were 3·85 and 1·2 cm (from Bagley *et al.*, 1985a).

starch gels is illustrated in Fig. 1. The results were plotted in the form given by eqn. (6); that is, as $f/2(\lambda - \lambda^{-2})$ versus $\lambda^{-1}$. The three curves in Fig. 1 correspond to the following experimental conditions: (a) gel bonded to the platens; (b) gel neither bonded nor lubricated; (c) gel/platen interface lubricated. The result obtained under lubricated conditions gave values of $(C_1 + C_2)$ in agreement with those obtained from simple shear and torsion experiments. Under conditions in which the sample was bonded to the platens the curve rose very steeply, and fracture occurred at the peak of the curve. This peak value of $f/2(\lambda - \lambda^{-2})$ in bonded compression was almost 20 times the value obtained under lubricated conditions. Under 'normal'

conditions, that is neither bonded nor lubricated (NBNL), the value of
$f/2(\lambda - \lambda^{-2})$ rose initially along the same curve as for the bonded
experiment. During this part of the compression the sample sticks to the
platens and thus behaves as if it were bonded, with values of $f/2(\lambda - \lambda^{-2})$ as
much as six times greater than those obtained under lubricated conditions.
At about $\lambda^{-1} = 1\cdot1$ the sample begins to slip along the platens and
$f/2(\lambda - \lambda^{-2})$ begins to drop, goes through a minimum and then rises to form
an asymptote to the curve obtained under lubricated conditions. The non-
bonded–non-lubricated (NBNL) curve always lies significantly above that
obtained in lubricated compression.

This result should not have been unexpected. Forster, in 1955, had
recognised the importance of frictional effects in compression work on
rubbers (Forster, 1955), although he did not compare the lubricated and
unlubricated cases. Culioli and Sherman (1976) and Vernon Carter and
Sherman (1978) made it abundantly clear in their work on cheese that
frictional effects can be crucial in compression studies. The reason for the
large quantitative effects observed lies in the change in sample shape which
occurs during compression when the sample sticks or is bonded to the
compressing platens. When sticking occurs, instead of a cylindrical sample
deforming under compression to a cylindrical sample of smaller height the
sample changes shape, becoming barrel-shaped. This change in shape is
demonstrated nicely in photographs of Gouda cheese during compression
(Culioli and Sherman, 1976). The barrel shapes were also observed during
compression of Leicester cheese (Vernon Carter and Sherman, 1978).
Culioli and Sherman show the quantitative changes they observed in the
force/compression curves for Gouda cheese when the compression was
carried out under lubricated conditions and when the sample/platen
interface was a high friction surface (emery paper). The effects were much
less than reported by Bagley et al. (1985a), and this may be due to slipping
and tearing of the Culioli and Sherman sample at the emery surface. Rate
effects are undoubtedly significant here, and in the work on Gouda cheese
deformation rates from $2\cdot5$ to 50 cm min$^{-1}$ were employed. These were
considerably higher than the deformation rates employed in the
experiments described in Fig. 1.

The results in Fig. 1 illustrate the advantages of comparing the response
of food materials to different testing modes. Not only can anomalies
occurring in one mode be uncovered but it may be possible to quantify the
magnitude of the unexpected effects. In the testing of gels as described
above, their behaviour in compression could be predicted from the simple
shear and torsion experiments. The expected curve was the one obtained

only under lubricated conditions. The results of the first experiment, which was carried out with the sample neither bonded nor lubricated, disagreed with this expectation and led to the investigation into the reasons for the discrepancies. Direct comparison, therefore, between bonded, lubricated and NBNL compression gives a clear indication of when slip/stick effects are occurring in NBNL experiments, and the quantitative evaluation of the effect of friction becomes possible.

## Quantitative Treatment of Effect of Change of Shape

It was surprising that the change in sample shape from a cylinder to a barrel shape caused such large effects. It has been possible to derive an expression to take account of this change of shape (Christianson *et al.*, 1985). With this analysis direct comparison of results of bonded and lubricated compression becomes possible (see also Casiraghi *et al.*, 1985). The magnitude of the correction is related to the fact that in lubricated compression the sample is in biaxial extension while in bonded compression, or when friction predominates or when the sample sticks to the platens, the material forms a parabolic bulge; the material in this bulge is under shear, and the consequences both for the stress–strain curves and for the fracture of the material can be quantified (Christianson *et al.*, 1985).

Figure 2 shows the changes in sample shape occurring under lubricated and bonded conditions. From the analysis (not confined to small deformations), using the procedure developed by Gent and Lindley (1959), the *corrected* stress, $\sigma_{BC}$, in the bonded condition is

$$\sigma_{BC} = \sigma_B \bigg/ \left[ 1 + \left( \frac{R_0^2}{2h^2} \right) \right] \tag{10}$$

where

$$\sigma_B = \text{force}/\pi R_0^2 \tag{11}$$

At a given strain $(\Delta h/h)$, $\sigma_{BC}$ versus $(\Delta h/h)$ should agree with the stress–strain behaviour in lubricated compression, with the stress in the lubricated case calculated as

$$\sigma_L = \text{force}/\pi R^2 \tag{12}$$

Figure 3 demonstrates the efficacy of the analysis. Note first that the same stress–strain curve is obtained in lubricated compression regardless of initial sample height (dotted line, Fig. 3, initial heights, $h_0 = 2\cdot0$–$4\cdot0$ cm). However, fracture occurs at smaller stresses with greater initial heights $h_0$. For bonded samples the stress $\sigma_B$ depends very significantly on initial sample height (Fig. 3, 'bonded' curves). Note the very large values of stress
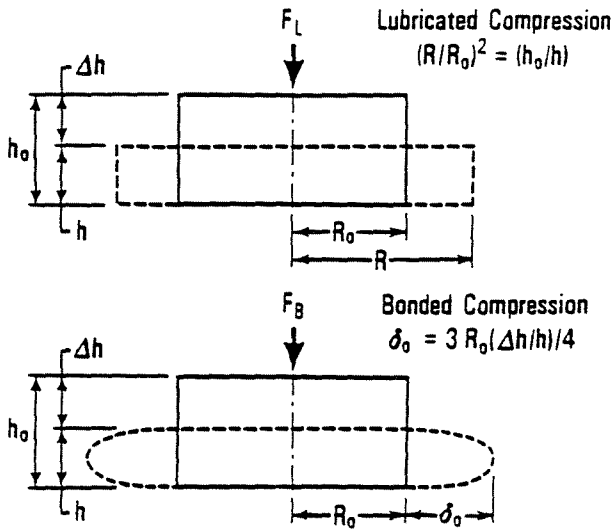
**Fig. 2** Deformation of cylindrical samples in lubricated and bonded compression: solid line, original elevation; broken line, deformed elevation (Christianson *et al.*, 1985).

compared to those for the lubricated cases. Correction of $\sigma_B$, however, by the term $(1 + R_0^2/2h^2)$ gives $\sigma_{BC}$ versus strain curves in good agreement with the lubricated compression experiments up to the point of fracture. In bonded compression, however, fracture occurs at lower stresses when corrected for shape change than in lubricated compression and, moreover, fracture stress *increases* with increasing initial sample heights from 1·2 to 4·0 cm for the bonded samples.

**Forging Theory Applied to Gels**
There appear to be many opportunities to apply concepts from mechanics of materials to problems in the testing of foods. A most interesting example is the application of forging theory to the determination of the modulus of alginate gels (Mohamed, 1983). Mohamed, referring also to the work of Olkku and Sherman (1979), notes that under compression a viscoelastic substance assumed a barrel shape and discusses in detail the stresses existing in the gel and develops equations for use with compression data. In the forging theory treatment the coefficient of friction is important and Mohamed comments that 'there is at present no generally accepted method of measuring the value of the coefficient of friction for given surfaces and lubricants', and has reported that as the frictional contribution to the applied force does not exceed 10–20% approximate values of the
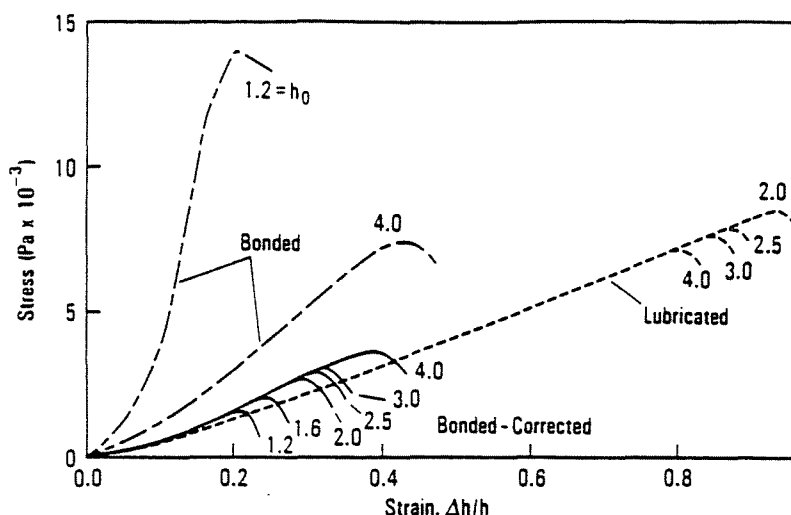
Fig. 3.  Stress ($\sigma_B$, $\sigma_{BC}$ and $\sigma_L$) versus strain curves for 10% wheat starch gels showing the agreement between the response in lubricated compression ($\sigma_L$) and the response in bonded compression corrected for shape change ($\sigma_{BC}$). The magnitude of the correction given by eqn. (9) is shown by the difference between the bonded and bonded-corrected plots. The difference in fracture behaviour under lubricated and bonded conditions is evident, the bonded-corrected fracture occurring at lower stress–strain levels than in lubricated compression (Christianson *et al.*, 1985).

coefficients suffice. In the materials examined by the author the frictional effects can exceed these limits and Mohamed's comment needs to be checked for each system examined. The advantage of bonding the sample to the platens is evident since the area of the sample in contact with the platens will then remain constant and the value of the coefficient of friction does not arise. Mohamed has also reported that it is easier to restrain the gel rather than attempt to ensure there is no friction between the gel and the platens, and that with air bubbles present Poisson's ratio will not be 0·5. This is a significant point, for which there seems to be little consideration in the literature. It means that the third strain invariant, $I_3$ (eqn. (3)), is not unity and the inclusion of a term involving $I_3$ in the strain energy function is necessary. Systems for which fuller investigation of volume effects might be warranted would be in the properties of bread and bread crumbs (Hibberd and Parker, 1985; Abu-Shakra and Sherman, 1984).

## Fracture Effects in Different Testing Modes
The value of complementary experimental methods is also clear in work on complex gel systems, as in the studies of Montejano *et al.* (1983, 1984a,b).

They studied selected comminuted-muscle gels and egg-white gels. Compressional deformation experiments carried out by this group are routinely made with the sample/platen interfaces lubricated to ensure reproducibility. They were primarily interested in fracture behaviour under gross deformation as being of prime significance in food texture determination, a concept in agreement with Jowitt's (1979) comments. In comparing beef and pork gels in compression and torsion, they found true shear stress, strain and modulus in agreement at fracture. Such agreement was not found with turkey gels in compression and torsion experiments for reasons which are unclear but, perhaps, are related to the fact that turkey gels need particularly large strains for fracture and there were very large shape changes prior to failure. The combination of two measurements is nevertheless most informative and should lead to a greater understanding of the meaning and significance of the results of each experiment.

A second advantage of having alternative experimental procedures is illustrated by the results of Montejano *et al.* (op. cit.) with the surimi gels. In uniaxial compression tests, failure did not occur even at axial strains of up to 97%! Surimi gels did fail in torsion, however, so that this alternative testing method for fracture behaviour was available to them. Similarly, in the work illustrated by Fig. 3, fracture was not observed in lubricated compression at initial heights less than 2 cm but occurred for all samples, regardless of height, under bonded conditions.

The minimum requirements for any investigation of material properties are that (i) the results should be reproducible and (ii) material properties should be independent of testing mode and sample dimensions. That dimensions can play a significant role was emphasised recently by Chu and Peleg (1985), and even when empirical tests are used it is essential to be aware of the possibility of results being dependent on sample size. This is a particularly important consideration for heterogeneous composite systems. Even if the material is isotropic, the particle size of the filler should be small compared to the sample size. If the filled system or composite system is anisotropic, the problems are compounded because attention must be given to the sample orientation during measurement. Fracture behaviour can depend on sample dimensions (see Fig. 3), and this feature of mechanical behaviour of foods warrants further consideration.

## COMPOSITE MATERIALS

Composite systems can include materials containing spherical or acicular fillers, or plate- or disc-shaped particles. Laminates, foams and honeycomb

structures are other examples of composite materials. Many foods can be regarded as composites. Many of the relevant papers are in the polymer composites, mechanics, physics and engineering literature. Jowitt (1979) made a clear plea for fuller application of the concepts from these other fields to problems of characterising, processing and understanding foods. To review all the relevant literature would be an awesome task but a few examples of recent work relevant to foods may be helpful. The work of Wu *et al.* (1985) deals with the modification of surimi gels by adding starch particles as fillers. Sharma (1984) considered the general criterion for structural failure of biological materials. Holt and Schoorl (1982) pointed out the rôle of mechanical failure in fruits and vegetables in relation to damage in processing and handling and to characterisation of textural properties. They developed failure diagrams to provide 'a sound conceptual framework for investigations of the mechanics of failure of fruits and vegetables'. A constitutive relationship for apple cortex was developed by Datta and Morrow (1984), choosing the apple as a 'logical choice as a source for specimens representing a composite, nonhomogeneous and anisotropic biological material'.

A good introduction to composite behaviour is given by Nielsen (1974), particularly in Chapter 7, Volume 2, where Fig. 3 shows the effect of the volume fraction of filler particles on modulus as well as the effect of incorporation of air as filler (foams). One interesting section deals with errors in determining the moduli of composites. Nielsen notes that many results in the literature are in error because of skin effects. In tests such as torsion or flexion the properties of the surface are 'emphasized at the expense of the interior', a point which can be of particular concern in foods. Chapter 8 of Nielsen's Volume 2 deals with fibre-filled and other composites, the discussion again being very relevant to the characterisation of foods such as meats which have a grain.

Occasionally, papers appear which, while rather esoteric and apparently remote from food systems, may have application to them. Thus, Mecham *et al.* (1983) discuss the solid particulates formed in standard diametral and axial impact tests of small cylindrical specimens of glasses. A correlation was found between the size distribution, plotted as straight lines on log-normal coordinates, the resultant descriptive characteristics and impact severity for both crystalline and vitreous specimens. Certainly, it would be expected that the sensory perception of brittle foods would depend on particle size and size distribution produced during mastication and so the methods discussed by Mecham *et al.* may provide some insight into new approaches for treating and testing brittle foods.

## Time Effects and Stress Relaxation

Materials classed as solids can show a wide range of time effects. Deformation of brittle foods may show little dependence on time, although the fracture properties of brittle materials may be dependent on rate of deformation. Other more complex foods in which rearrangement of structural units, cross-links, etc., may occur under stress or deformation will exhibit more marked time effects. Most solid food materials are biologically active (Peleg and Pollak, 1982), but the consequent time effects will not be considered here. Physical instability which occurs under stress or strain imposed on the material (so that mechanical equilibrium is not readily attained) is the subject of concern here. Such instability means that in deforming a sample, as in an Instron test, the stress–strain curve depends on time, and hence on the rate at which the sample is being deformed. Similarly, if a given strain is imposed on a sample, the stress decays with time (stress relaxation). Alternatively, if a given stress is imposed, the deformation changes with time, i.e. the material will creep. (See, for example, Mitchell and Blanshard (1976a,b).) It is sometimes difficult to distinguish a solid from a very high viscosity liquid,* but Peleg and Pollak (1982) remark that 'the mathematical distinction between solid and liquid is very clear. It reduces to the simple question of whether the stress of a deformed specimen approaches (though asymptotically) a zero or a finite level'. They go on to remark that it may be difficult to determine experimentally whether the infinite time stress is zero or not. For instance, doughs, which are classified as viscoelastic fluids, retain stresses in a relaxation experiment for as long as several hours. Doughs, as with other foods, have a very broad distribution of relaxation times and this is reflected in complex stress/time/strain relations.

In a stress relaxation experiment an instantaneous deformation is imposed on the material and the resultant stress is measured as it decays with time. There are a number of ways to treat such data. For example, Feltham (1955) shows that for a wide range of materials for which a log-

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* It is futile to fret over whether a thing fits into only one or the other man-made category, particularly when such categories are defined in ways which are not mutually exclusive, as is often the case with definitions of 'solid' and 'liquid'. Although it is possible to define solid and liquid in ways which are less conducive to confusion or uncertainty than those which depend on a particular response to *stress* or *strain*—especially if they omit *time* from the definitions—it is possible to avoid such dilemmas entirely by referring to 'solid properties' or 'liquid properties' (or to 'elastic properties' or 'viscous properties') of materials and recognise that most materials—certainly most *food* materials—may, under appropriate conditions, possess either, or both.—Ed.

normal distribution of Maxwell elements is assumed, probability plots can be used to characterise the relaxation process. Feltham also refers to early work in the polymer area on alternative methods of examining and analysing relaxation data.

For relatively solid materials there may be little time dependence but many foods, because of structural changes or rearrangement when strained, may show marked time effects. The question that arises about such material is how instantaneous can a deformation be? The assumption of an 'instantaneous deformation', a step-function strain, may not be a good one. This can be a particularly serious problem in the study of large deformation effects since the imposition of a large deformation is obviously more time-consuming than imposing a small deformation. How does the time to deform, $t_1$, affect the relaxation curve? Although in principle the time $t_1$ can be made as small as is wanted, the resultant high deformation rate may break the sample, and there are always concerns about the response time of recorders and transducers or other deformation- and force-measuring devices. So, for solid food systems whose relaxation behaviour is significant, account must be taken of the effect of deformation time on the subsequent relaxation behaviour.

This is not an easy problem to deal with. If the material is described by an appropriate constitutive relationship, the required calculations can, in principle, be carried out; but such an equation is usually not available. For linearly viscoelastic materials, Meissner (1978) recently published a procedure. He suggests a simple procedure to obtain linear viscoelastic material functions for both polymeric solids and liquids which avoids the 'factor-of-ten rule' for short relaxation times. This author is not aware of any applications of this procedure to food materials, many of which are beyond doubt non-linear systems; in addition, the strains imposed are not imposed at a constant strain rate, one of the requirements of Meissner's method.

Peleg (1979, 1980b) and Peleg and Normand (1983) suggested representation of short-term relaxation data as

$$\frac{F(0)t}{F(0) - F(t)} = k_1 + k_2 t$$

where $F(0)$ is the force at time $t = 0$, $F(t)$ is the force at time $t$, and $k_1$ and $k_2$ are constants. This relationship has been used successfully by others, for example by Masi and Addeo (1984), in studies on mozzarella cheese. In systems to which the author has applied the procedure, the plots always show two regions of different behaviour, as is also the case with the

probability plots after Shelef and Bousso (1964). Two sets of constants are therefore needed to describe the material by either of these methods. More significantly, the fitting terms are dependent on rate of testing, and so a degree of complexity is introduced which appears, in principle, to be related to the dependence of relaxation data on the time to deform. These types of plots are, nevertheless, worth examining, but to study the fundamental issue of the effect of deformation time other approaches appear to be necessary.

One method worth examining is an older procedure proposed by Zapas and Phillips (1971) and Zapas and Craft (1965). This work is an application of the Bernstein–Kearsley–Zapas incompressible elastic fluid theory and illustrates the use of the theory both in calculating stress/strain response for a number of simple extension histories from single-step relaxation data and procedures for comparing a material's responses after different deformation times. Their applications were to elastic fluids and rubber-like solids such as cross-linked elastomers and plasticised polyvinyl chloride. The author and his colleagues have carried out experiments on food systems for which the procedure seems applicable but the results are at a preliminary stage. It does seem, however, that the method is worth pursuing both for solid-like and semi-solid foods and for highly viscous and elastic systems such as doughs.

## Friction

As discussed earlier, uniaxial compression of a food will give results which, in general (platen/sample interfaces neither bonded nor lubricated), will depend on both the frictional properties of the interface and the bulk properties of the material under test. While frictional effects can be eliminated (lubricated compression) or maximised (bonded), the frictional properties are important in affecting sensory effects in the mouth. The importance of frictional effects is recognised and has been discussed by Voisey and de Man (1976), Bourne (1976), Culioli and Sherman (1976) and Vernon Carter and Sherman (1978). The subject is also of significance to the polymer area, and attention can be drawn to the work of Gent (1974) and Gent and Henry (1982). Frictional effects must also be considered in food extrusion where some systems exhibit plug flow with the extruder output being determined by the coefficient of friction between the extruder metal and the food plug (Jasberg *et al.*, 1979). They have found a relationship between coefficient of friction and percentage moisture which is linear within the range from 10 to 40% moisture. Gent commented to the authors that this simple relationship was unexpected and raised concerns regarding

general problems in evaluating the coefficient of friction and the vital role played by total pressure and other variables which can significantly affect the results. Gent's concern is exacerbated in foods where mouth feel depends in part on frictional effects which in turn are modified by the presence in the mouth of saliva and by pressure and temperature.

## CONCLUSIONS

The determination of the mechanical properties of solid foods is a difficult and demanding task for the food scientist because of complexity of food structure and composition. For brittle foods there are opportunities to apply concepts from the field of composite and polymeric materials as noted by Jowitt (1979). For softer solids frictional and relaxation effects deserve greater attention. Friction plays a significant rôle in compression testing and in texture profile analysis and is, therefore, a significant factor in evaluating sensory attributes of foods. Relaxation effects are difficult to ascertain, and more fundamental studies of testing rate and deformation time are necessary. Fracture behaviour, and particularly differences in fracture stress in different testing modes, deserves more attention. For brittle foods this would include size and shape distribution of the fragments after fracture.

More work on frictional effects in the mechanics of solid foods is indicated, but relatively little work is available. Attention can be drawn to a method proposed by Atkin and Sherman (1984), who examined the effect of sample diameter-to-length ratios and the resultant differences; where the $D/L$ ratio increased, the relative effect of friction decreased. The observations may have implications for sensory evaluation of firmness.

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# DISCUSSION

*D. A. E. Ehlermann* asked if Bagley's equations were appropriate to compare relaxation results from different laboratories using different deformation rates and, if the only instrument available were relatively slow-moving, could any information on high rates of shear be extracted from its results, e.g. in relation to chewing. *E. B. Bagley* reiterated that there was no problem in dealing with results from rapid deformation–relaxation tests. The direct results were valid. However, the deformation *history* of a slowly deformed specimen profoundly affected its relaxation behaviour and he did not think that results from such tests were of use in predicting the behaviour of the same material in relaxation after rapid deformation. Calculations would be more useful. *J. de Baerdemaeker* asked if the *failure* pattern of lubricated and non-lubricated samples was different, as the stresses might be greater locally in bulges and so the actual local failure stress might be the same in both cases. *Bagley* confirmed that there were differences, the bonded specimens appearing to fail in shear, the lubricated ones in tension of some form. This is illuminated by their preliminary work on specimens containing holes, a condition requiring further study.

*H. Schubert* asked how non-uniform materials should be dealt with. *Bagley: Inhomogeneous* materials should be tested in samples large enough for the scale of inhomogeneity to be small in comparison, so that the results were independent of sample size. *Anisotropic* materials, on the other hand, just had to be tested in the different directions in which the properties were different, in order to characterise the material completely. These were complex materials and had to be dealt with accordingly.